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SRM-ASSISTED TRAJECTORY FOR THE GTX REFERENCE VEHICLE

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ABSTRACT

A goal of the GTX effort has been to demonstrate the feasibility of a single stage- to- orbit (SSTO) vehicle that delivers a small payload to low earth orbit. The small payload class was chosen in order to minimize the risk and cost of development of this revolutionary system. A preliminary design study by the GTX team has resulted in the current configuration that offers considerable promise for meeting the stated goal. The size and gross lift-off weight resulting from scaling the current design to closure however may be considered impractical for the small payload. In lieu of evolving the project's reference vehicle to a large-payload class, this paper offers the alternative of using solid-rocket motors in order to close the vehicle at a practical scale. This approach offers a near-term, quasi-reusable system that easily evolves to reusable SSTO following subsequent development and optimization.

This paper presents an overview of the impact of the addition of SRM's to the GTX reference vehicle's performance and trajectory. The overall methods of vehicle modeling and trajectory optimization will also be presented. A key element in the trajectory optimization is the use of the program OTIS 3.10 that provides rapid convergence and a great deal of flexibility to the user. This paper will also present the methods used to implement GTX requirements into OTIS modeling.

INTRODUCTION

One goal of the GTX design effort is the generation of a 300 lb payload class SSTO conceptual vehicle of small size and weight. Small vehicles obviously require much less structure and therefore cost less to build and operate. The use of expendable external rockets can overcome shortcomings in propulsion or materials performance, and the vehicle concept can still evolve into a meaningful single stage to orbit vehicle. In effect, the GTX design team wanted to maintain a small vehicle, augment the thrust of the vehicle, and avoid deviating significantly from a single stage concept. An almost obvious design choice is the use of an existing solid rocket motor system that could be added to GTX without significantly disturbing critical flow paths, adding any more weight than absolutely necessary to accommodate the added thrust loads, and still allow the vehicle to steer. The GEM 46 solid rocket motors proved to be a good match for GTX. These motors are flight qualified having flown on the Delta III vehicle, have thrust vector controls, and appear to be readily available.

In reference [1], Hack and Riehl present the methodology and models then used to simulate the GTX reference vehicle. Although that report addressed an earlier configuration of the vehicle, the methods, figures of merit, and problem solving approach remain the same.

SYMBOLS

A^*	Rocket Engine Throat Area
A_c	Vehicle Inlet Capture Area
I_{sp}	Specific Impulse
M	Mach number
P_0	Atmospheric Pressure
P_4	Duct Pressure
Pc	Rocket Engine Chamber Pressure
q	Dynamic Pressure
T	Net Thrust
W_f	Final Weight
α	Angle of attack (deg)
γ	Flight Path Angle w.r.t. horizontal (deg)

ACRONYMS

OTIS	Optimal Trajectories by Implicit Simulation Computer Program
RJ	Ramjet Engine
RAM	Ramjet Engine
SRM	Solid Rocket Motor system
SC	Supersonic Combustion Ramjet Engine
SCRAM	Supersonic Combustion Ramjet Engine

GTX PROPULSION

In reference [2], Trefny describes the GTX RBCC propulsion in detail. Here we will briefly summarize the baseline GTX flight sequence and the various operating modes of the vehicle.

The RBCC engine operates in four distinct modes. These modes, in the order that they occur in flight are:

1. Combined-Cycle (Rocket/Ram)
2. Ramjet (RJ)
3. Scramjet (SJ)
4. Rocket.

The RBCC engine design is an integrated flow path that uses liquid oxygen and hydrogen propellants. An axisymmetric engine design is used to maximize the structural efficiency as well as to reduce some engine analysis uncertainties. Nozzles are integrated into the vehicle aft end in order to act as an expansion surface when operating at high speeds. An altitude compensating effect is provided by this arrangement at low speeds.

The GTX launch vehicle employs three RBCC engine pods distributed 120° apart along the longitudinal axis and terminate at the rear of the vehicle. Figure 1 shows an isometric of the GTX with the GEM 46 SRM's and figure 2 shows the same vehicle in a three-view drawing with dimensions in inches.

ANALYSIS METHODOLOGY

All of the flight design and trajectory optimization analyses reported herein were generated with version 3.10 of the computer program OTIS—Optimal Trajectories by Implicit Simulation references [3 and 4]. OTIS implicit integration mode (also known as OTIS mode 4) was used exclusively. Implicit integration (or collocation) is used to simultaneously optimize and integrate the state differential equations. The states and control variables are represented by piecewise polynomials. The optimal control problem is then transcribed to a nonlinear programming problem via the implicit integration scheme. This is then solved by the nonlinear programming package SNOPT. To verify the converged trajectory, OTIS generates an explicitly integrated (4th order Runge-Kutta fixed step size) trajectory using the control history from the implicit solution.

All vehicle modeling reported herein used only three degrees of freedom without any attempt to verify trim in the pitch plane.

Flight path equations of motion were used for this problem just as in previous simulations without the SRM thrust augmentation. Additionally, flight path controls are used instead of Euler angle controls because of the aerodynamic flight involved in the problem. However, the only flight path control angle used in this study is the angle of attack, α, positive being nose up. The planar flight assumption yields zero bank and sideslip angles.

FIGURES OF MERIT

The primary figure of merit (FOM) for RBCC ascent trajectories is the weight of the vehicle in its final orbit, W_f. OTIS maximizes final weight, which in effect minimizes propellant.

The overall ratio of oxidizer to fuel weights for the entire vehicle, O/F, provides a second figure of merit. This parameter is used to compare the effects of constraints on the split between the oxidizer and the fuel.
The reader should note that the OTIS program does not directly compute O/F ratio. This is computed after the fact in post-processing software.

CONTROLS

Angle of attack, α, is the primary means of control for the RBCC trajectory optimization. This is an independent variable for all phases of powered flight after the vertical rise. During the vertical rise and during both atmospheric and vacuum coasts, α is set to zero to insure that drag is as small as possible. Angle of attack is limited to be within ±6° for modes 2 and 3 to insure sufficient inlet flow based on vehicle configuration.

The chamber pressure, P_c, in the rocket element during combined-cycle mode and full rocket mode is also a time varying control variable. Near take-off, the chamber pressure is higher to minimize the time in low speed flight. As velocity increases and the vehicle approaches the point where the ramjet mode can take over, the chamber pressure is allowed to decrease to 20% of the maximum. For this report, the maximum rocket chamber pressure is 2000 psi. In combined-cycle, the chamber pressure is constrained to always decrease. In rocket mode, the chamber pressure may also vary to down to 20% of the maximum to limit the acceleration of the vehicle. The baseline vehicle requires maximum chamber pressure to produce sufficient thrust for takeoff. For the thrust-augmented case, chamber pressure was optimized during the lift off of the vehicle to optimally match air breathing propulsion and the SRM propulsion.

The duration of each propulsive mode is unspecified and open for optimization. As a practical matter, the mode durations are bounded by input to OTIS to insure good mathematical problem

definition for the optimizer. Lastly, the initial azimuth after pitch-over, Ψ, is also open for optimization, but with $0 \le \Psi \le 90°$.

CONSTRAINTS

The most significant constraint on the trajectory is the maximum dynamic pressure, q. This constraint affects the amount of heating and the pressure loads that the vehicle endures and sizes the thermal protection system, a significant vehicle design driver. The maximum dynamic pressure allowed over the entire trajectory is 1500 lb/ft^2. The minimum dynamic pressure for RJ/SJ mode is 500 lb/ft^2 in order to sustain combustion. From a trajectory standpoint, the vehicle cannot stay too low in the atmosphere while accelerating, as dynamic pressure becomes too high.

Each engine mode is limited to operate within specified Mach number ranges. These ranges are shown in Table 1. Although the OTIS program enforces these ranges, actual mode transitions occur at Mach numbers that optimally provide the maximum benefit to maximizing final weight. A 10-atmosphere constraint on duct pressure prevents OTIS from selecting a flight regime that would induce internal vehicle pressures greater than can reasonably be accommodated by the vehicle structure.

The vehicle is constrained to a maximum total acceleration of four times gravity (4 g's) throughout ascent. This limitation tends to reduce the overall structural mass and prevents inducing loads on payloads beyond that typically found on existing launch systems. The vertical rise must be at least 500 feet to insure that any launch tower is cleared before controlled flight begins. Finally, the planar flight assumption yields zero bank and sideslip angles for the entire ascent.

MODELS AND ASSUMPTIONS

The trajectory optimization process requires a substantial amount of information about the propulsion modes and flight characteristics of the vehicle. This section discusses the types of data required by OTIS and how it is utilized.

Propulsion Models

SRM

The thrust profile for the three GEM 46 motor is shown in figure 3. The I_{sp} is 277.8 secs. and the total exit area is 22.3 ft^2. For simulation purposes in OTIS, this thrust versus time history is represented by a quintic chamfered spline. This representation provides the accuracy of linear interpolation while providing second order "smoothness." The spline is called chamfered because it rounds off the "corner" where linear interpolation segments meet.

Mode 1 (Rocket-ramjet)

The thrust and Isp in mode 1 are modeled as function of chamber pressure, atmospheric pressure, and Mach as follows:

$$T = A^* P_c f_{T1}\left(M, \frac{P_c}{P_o} \right)$$

$$Isp = f_{I1}\left(M, \frac{P_c}{P_o} \right)$$

where A^* is thruster throat area in ft^2, P_c is chamber pressure in lb/in^2, P_0 is atmospheric pressure, and the functions f_{T1} and f_{I1} represent mode 1 interpolating functions for the tabular data representations of GTX propulsion. OTIS interpolates this data using quintic or linear spline fits as appropriate in the dimensionality of the data. Total capture area for the GTX vehicle, A_c, is 138.2 ft^2 and A^* is .942 ft^2.

Modes 2 and 3 (Ramjet and Scramjet)
The thrust and Isp for the ramjet and scramjet are calculated by similar relationships:

$$T = qA_c f_{TN}(M)$$
$$Isp = f_{IN}(M)$$
$$P_4 = f_{IN}(M)$$

These two engine operational modes have distinct tabular data, one for thrust coefficient, one for specific impulse, and one for the duct pressure (P_4). These are represented above as f_{TN} and f_{IN} where N=2 or 3.

Mode 4 (Rocket)
The rocket mode propulsion parameters are given as functions of engine throat area and chamber pressure.

$$T_{vacuum} = A^* P_c f_{T4}(P_c)$$
$$Isp = f_{I4}(P_c)$$

Here again f_{T4} and f_{I4} are mode specific interpolating functions for thrust and Isp. An atmospheric backpressure correction term is added to the rocket mode thrust value but has minimal impact to performance:

$$T = T_{vacuum} - A_{exit} P_O$$

Rocket mode mixture ratio is also given as a tabular function that represents the impact of secondary flows within the engine that do not produce thrust. Hence the nominal mixture ratio of 7/1 results in a mixture ratio of 6.77/1 for instance.

Aerodynamic Model

Similar to the propulsion model, tables for the coefficients of lift, C_L, and drag, C_D, are provided to OTIS. The APAS program reference [6] generated these coefficients for both the nominal configuration and the thrust-augmented configuration. In both cases, the data table interpolations are functions of angle of attack and Mach number. For the GTX configuration 10c used in this analysis, the reference area, S_{ref}, is 188.84 ft^2.

Earth Atmosphere and Gravitational Models

The atmosphere model used for this study is the U.S. Standard Atmosphere, 1976. A quintic spline version of this atmosphere is used instead of direct evaluation in order to insure continuous first derivatives of the force terms affected by the atmosphere. No additional wind conditions are added to this model. Above 400,000 feet in altitude, the atmospheric model is set to a vacuum. In vacuum, the Mach number calculations use the speed of sound at standard sea level. Earth's

Gravitational potential was assumed to be 1.40785E+16 ft^3/sec^2 with an equatorial radius of 6378.14 km or 20,925,656 ft.

MAPPING PROBLEM TO ANALYSIS TOOL

Within OTIS, a phase is defined as a segment of the trajectory with similar flight, aerodynamic, and propulsive characteristics. A number of trajectory nodes are placed within a phase. These are the points at which the implicit integration occurs. More nodes can increase precision but at the expense of longer the run-time.

Table 2 lists controls and path constraints as given in Trefny reference [5] that are active within each operating mode. These constraints and bounds apply to the OTIS phases of both the baseline simulation and the thrust-augmented simulation. These two simulations differ in their structure so that the thrust-augmented simulation ends precisely at SRM depletion, the use of SRM thrust is stopped and in a subsequent OTIS phase, the burned out SRM boosters are jettisoned. From thereon to orbit insertion, the simulations are identical.

MISSION AND FLIGHT SEQUENCE OF THE THRUST AUGMENTED VEHICLE

The baseline mission utilized for this study is the planar ascent of the GTX vehicle to a 220 Nmi orbit at 28.5° inclination.

The SRM’s ignition begins the flight of the thrust-augmented GTX. The RBCC’s first operational mode, rocket-ramjet, is also operating and generating thrust. The chamber pressure is not at its maximum value as in the baseline GTX, but at a value determined that maximizes on-orbit (final) weight. Operating in this mode, the vehicle begins with a vertical rise followed by a pitch-over. The vehicle accelerates through the transonic region until reaching a speed where ramjet combustion can be sustained. The rocket-ramjet mode is not nearly as efficient as the ramjet mode. So one objective of the trajectory optimization process is to determine the best flight conditions for where the handoff between Combined-Cycle and ramjet occurs. The GEM 46 stops producing significant thrust at 77 seconds. At 80 seconds into the flight the SRM’s are presumed to have burned out completely. They are jettisoned and the GTX core vehicle continues its flight.

The ascent continues in ramjet mode as the vehicle accelerates, eventually switching to supersonic combustion ramjet mode. These middle two operational modes use only atmospheric oxygen, further reducing the on-board oxygen storage requirements. As such, they are the most efficient segments of the ascent. OTIS maximizes the use of these stages while satisfying associated path constraints.

Finally, a pure rocket mode, using stored LOX, takes over and accelerates the vehicle through the atmosphere. The rocket is throttled to achieve the acceleration constraints on the trajectory. This, in turn, decreases the weight of the structural subsystem. After orbital insertion velocity is achieved, the vehicle coasts to just below the final orbit altitude, where a circularization burn in rocket mode occurs, ending the ascent simulation.

PERFORMANCE COMPARISON OF BASELINE MISSION AND THE THRUST AUGMENTED MISSION

The gross liftoff weight of the baseline vehicle is 236,000 pounds while the addition of the three SRM’s increases this weight to 360,770 pounds for the thrust-augmented vehicle. The extra weight comes from the three loaded GEM 46 SRM’s exclusively.

Tables 3 and 4 present summaries of key trajectory events and performance for the baseline and the thrust-augmented cases, respectively. In each table the baseline value is presented above the thrust-augmented value. In table 3 one can see that the thrust-augmented case rises faster and transitions into the first three propulsion modes sooner than the baseline case. This is as expected, but these faster transitions come at the expense of altitude attained relative to the baseline vehicle. It remains in mode 3 longer than the baseline to take complete advantage of the more efficient air breathing modes longer than the baseline even though the transition to mode 4 occurs at the same Mach number. The first rocket burn is some seven seconds longer because the thrust-augmented vehicle is heavier than the reference at the start of the burn and lower in altitude. Atmospheric coast to the second rocket burn (orbital injection burn) takes longer because OTIS has found a different transfer orbit (apogee altitude = 224.3 x perigee altitude = –92.9 Nmi. nominally vs. 228.5 x –46.2 Nmi. for the thrust-augmented case). The final altitudes of the nominal and thrust-augmented cases differ slightly because OTIS converges to a specified tolerance on final apogee and perigee altitude (220 ± 0.5 Nmi.) over a non-spherical earth.
In table 4 one observes that the thrust-augmented vehicle uses about the same amount of hydrogen to get on orbit and considerably less oxygen. The rocket only mode (mode 4) requires more oxygen and hydrogen than the baseline simply because the vehicle weighs more at the start of the mode.

Figures 4 to 13 show comparisons between the baseline and the thrust-augmented vehicles' key trajectory parameters. Note that the angle of attack history exhibits a series of rapid oscillations in mode 3 that persist even after an integral compensation feature was employed to remove them. Also limiting the rate of change in angle of attack produced less final weight. One can only conclude that the resolution of the propulsion and aerodynamic data and implicit integration scheme have coupled in such a way as to produce these oscillations in the vicinity of a truly optimal solution. With this sole exception there is little that is unexpected in the ascent of the thrust-augmented vehicle relative to the nominal. Vehicle constraints in dynamic pressure and total acceleration are met while always transitioning from engine mode to engine mode at the appropriate Mach number.

One can reasonably conclude that the thrust-augmented GTX will supply the added weight on orbit that is desired. The final weight represents 24.5% of the initial GTX weight of 236,000 lbs. as opposed to the nominal vehicles 20.7%. The extra margin could absorb future weight and performance shortfalls.

SUMMARY

Thrust augmentation using the GEM 46 provides the additional weight on orbit that the GTX design team sought without significantly compromising the intent of single stage to orbit transportation. These SRM's are flight qualified, available, and steerable. There installation on the GTX conceptual vehicle appears to be straightforward.

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Table 1. RBCC ENGINE MODE CONSTRAINTS

Engine Mode	Minimum Mach	Maximum Mach	Minimum Duct Pressure (Atm.)	Maximum Duct Pressure (Atm.)
Combined-Cycle	–	3	N.A.	N.A.
Ramjet	2.5	4	0.5	10
Scramjet	5	15	0.5	10
Rocket	4	N.A.	N.A.	N.A.

Table 2. SIMULATION CONTROLS AND PATH CONSTRAINTS

	Mode 1		Mode 2		Mode 3		Mode 4	
	Min	Max	Min	Max	Min	Max	Min	Max
Freestream dynamic pressure, Q_0 (psfa)	500	1500	500	1500	500	1500	500	1500
Angle-of-attack, α (degrees)			–6	6	–6	6		
Thruster chamber pressure, P_c (psia)	400	2000					400	2000
Diffuser exit pressure, P_4 (atm)			1/2	10	1/2	10		
Total acceleration (g's)		4		4		4		4

Table 3. KEY MISSION EVENTS FOR THE BASELINE AND THRUST AUGMENTED VEHICLES

Flight Phase	Time (sec)	Altitude (ft)	Altitude (Nmi)	Relative Velocity (ft/sec)	Mach	Weight (lb)
Liftoff	0 0	0 0	0 0	0 0	0 0	236,000 360,770
End of Vertical Rise	6.1 5.35	500 500	0.08 0.08	163 191.4	0.15 0.17	229,027 347,003
Mode 1–2	65.1 53.5	43,015 43,015.3	7.1 7.1	2414.5 2414.5	2.5 2.5	174,017 240,633
End SRM	N.A. 80	N.A. 62,696.2	N.A. 10.3	N.A. 3801.5	N.A. 3.9	N.A. 217,134 then 203,700
Mode 2–3	149.6 114.3	78,277 72,242	12.9 11.9	5,374 4,868.6	5.5 5	167,455 201011
Mode 3–4	613.5 617.3	122,443 112,838	20.2 18.6	11,183 10,821	10.9 10.7	133,314 169,659
End of 1st rocket burn	720.3 731.8	228,321.5 217,737.4	37.6 35.8	24,568.5 24,673.2	25.1 24.7	50,996.5 59,937.5
Start 2nd rocket burn	2,201.8 2,421.8	1,340,829.8 1,322,160.8	220.7 221.2	23,160.4 23,245.3	20.7 20.8	50,996.5 59,937.5
End	2,209.8 2,429.9	1,340,940.2 1,344,223.2	220.7 221.2	23,731.8 23,729.4	21.3 21.3	48,827.9 57,769.1

Table 4. PROPELLANT BREAKDOWN FOR THE BASELINE AND THRUST AUGMENTED VEHICLES

Engine Mode	Oxidizer Weight (lb.)	Fuel Weight (lb.)	Total Propellant (lb.)	O/F Ratio
Mode 1	52,038 24,693	9,533 5,415	61,571 30,108	6.34 (aver.) 5.90 (aver.)
Modes 2 and 3	0 0	34,125 36,104	34,125 36,104	N.A. N.A.
Mode 4	79,003 97,207	11,671 14,360	90,674 111,567	6.77 6.77
Total	131,041 121,900	55,329 55,879	186,370 177,779	2.37 2.18

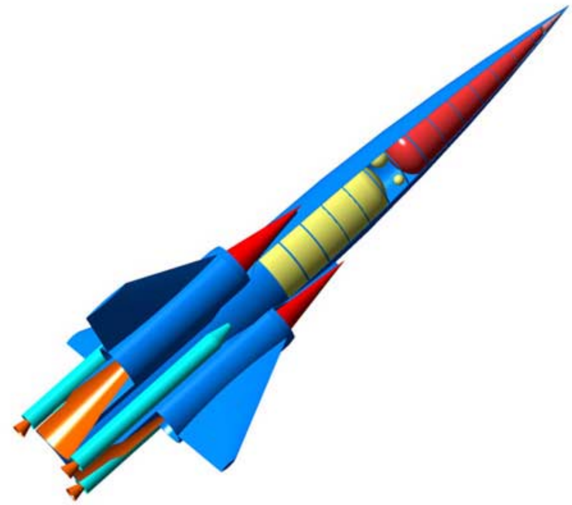

Figure 1. Isometric view of GTX with SRM added

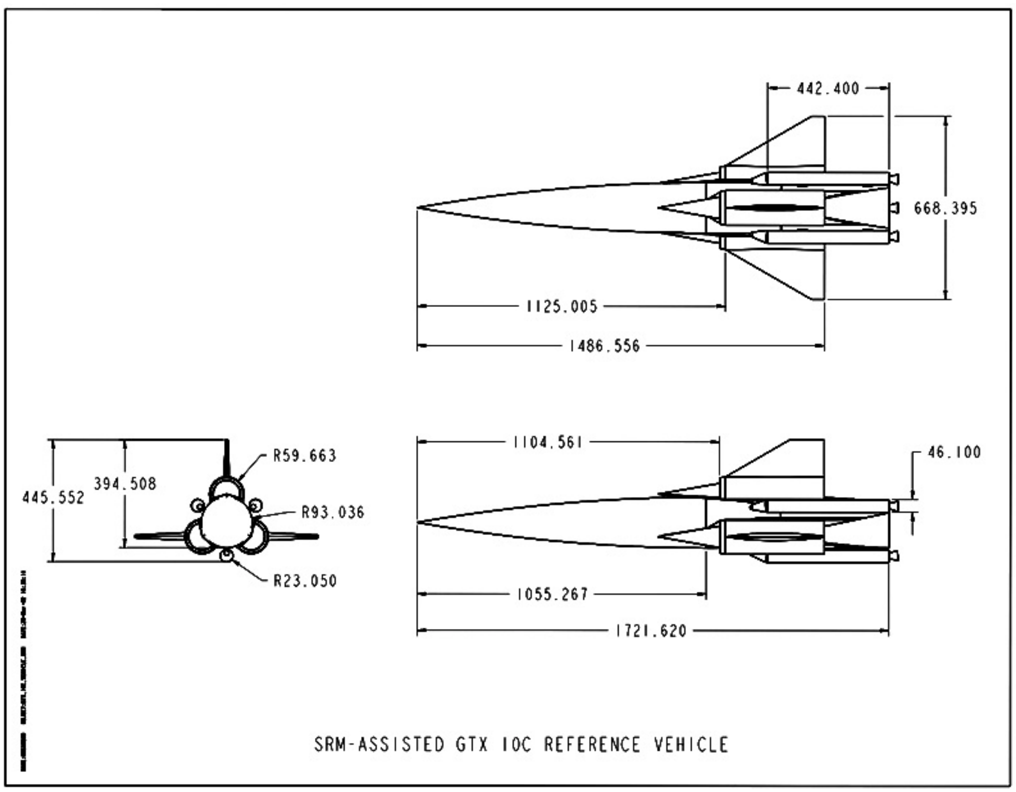

Figure 2. Three-View of GTX 10C with GEM 46 SRM's

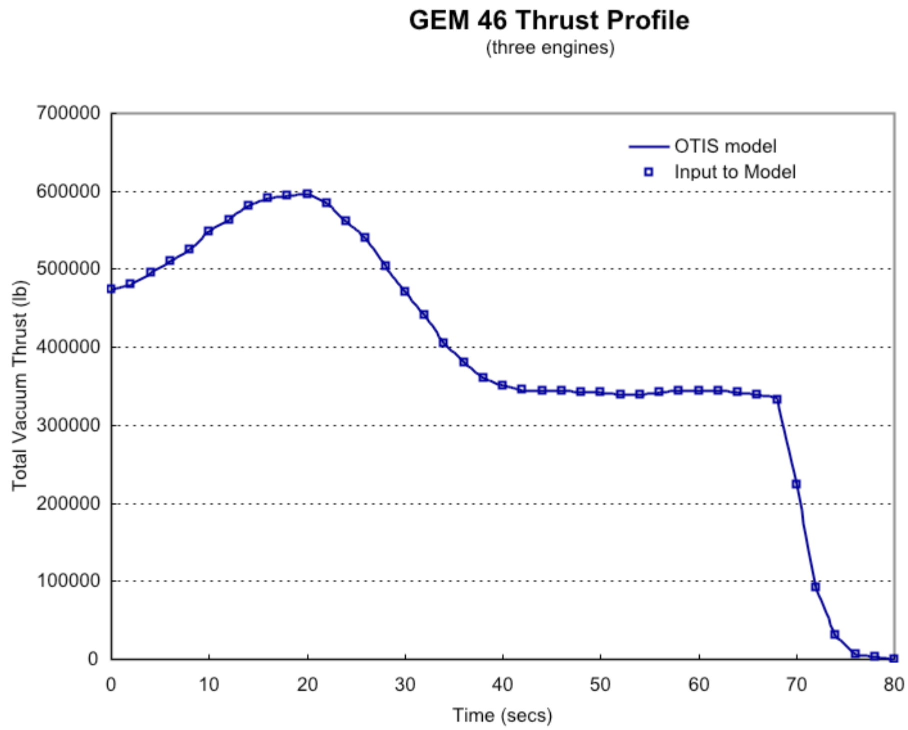

Figure 3. GEM 46 thrust profile

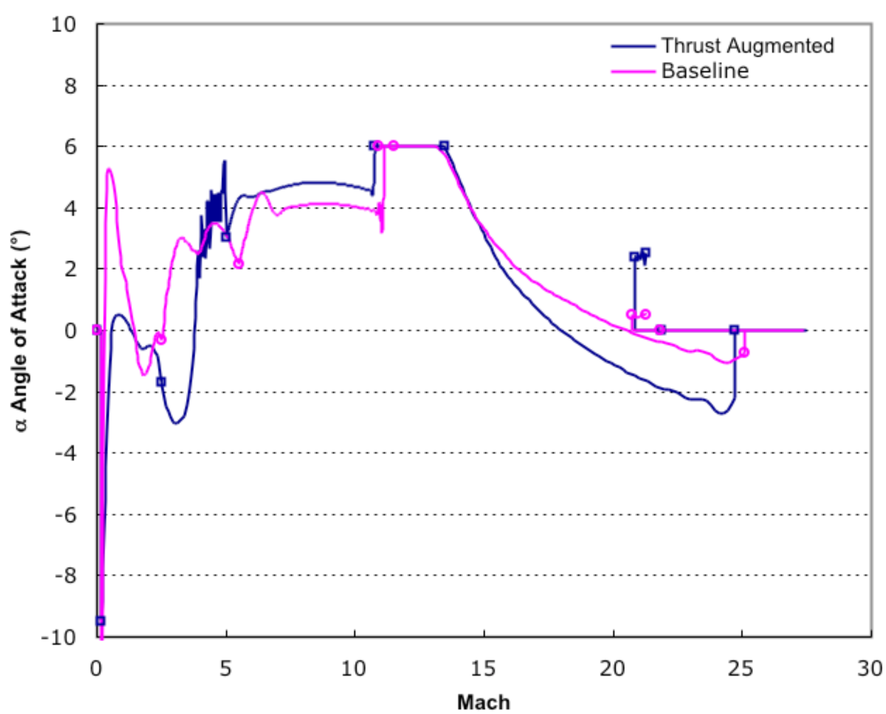

Figure 4. Angle of Attack vs. Mach

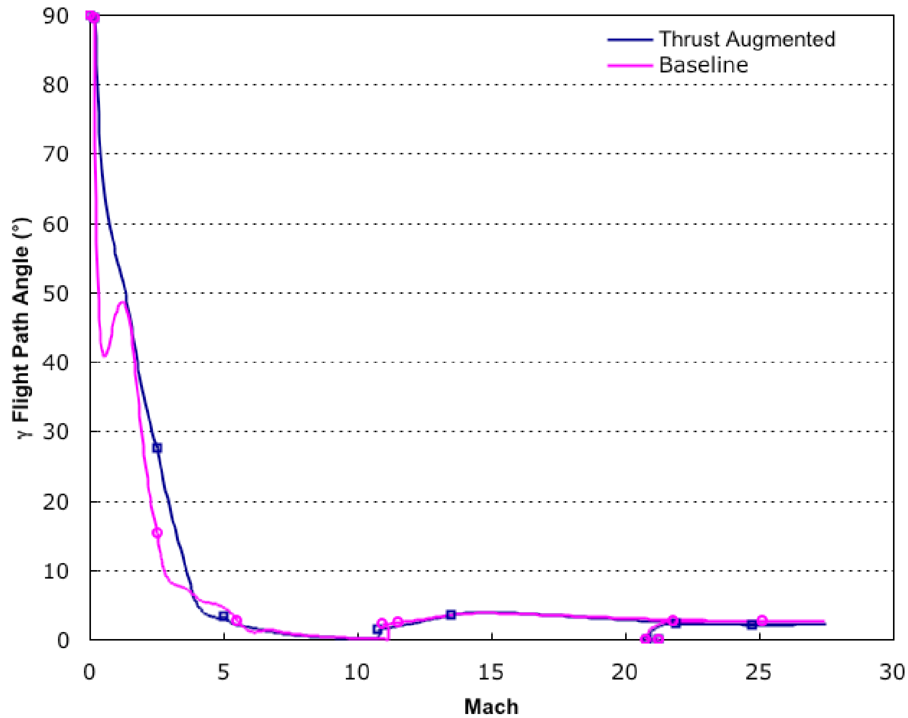

Figure 5. Flight Path Angle vs. Mach

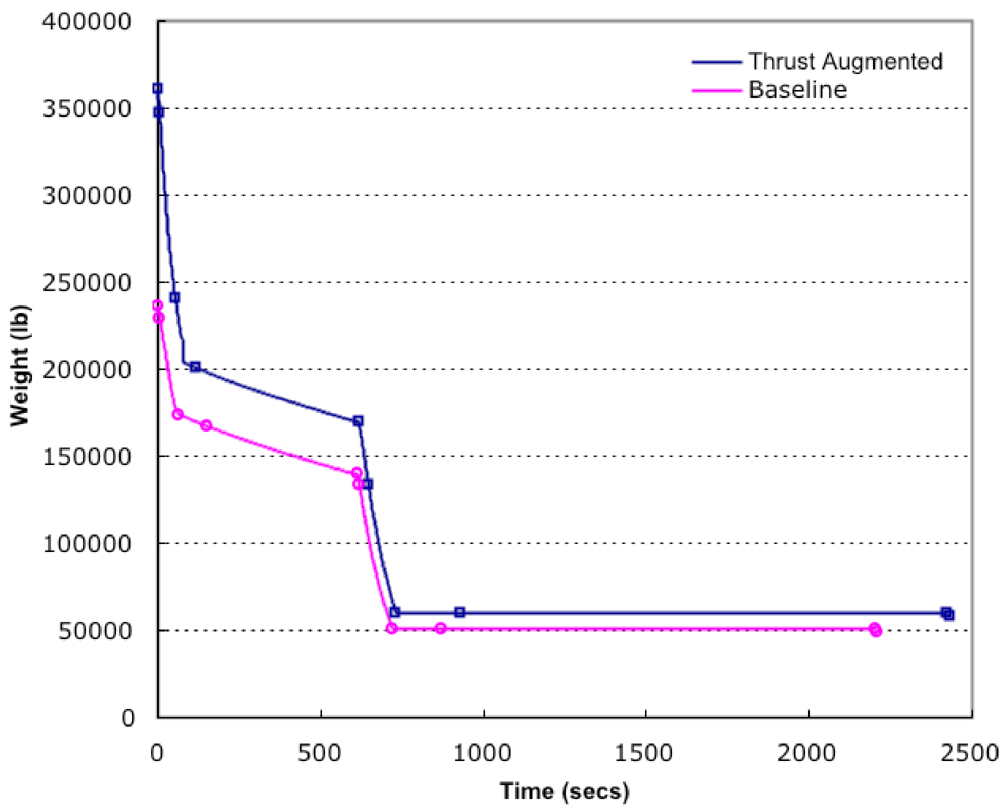

Figure 6. Weight vs. Flight Time

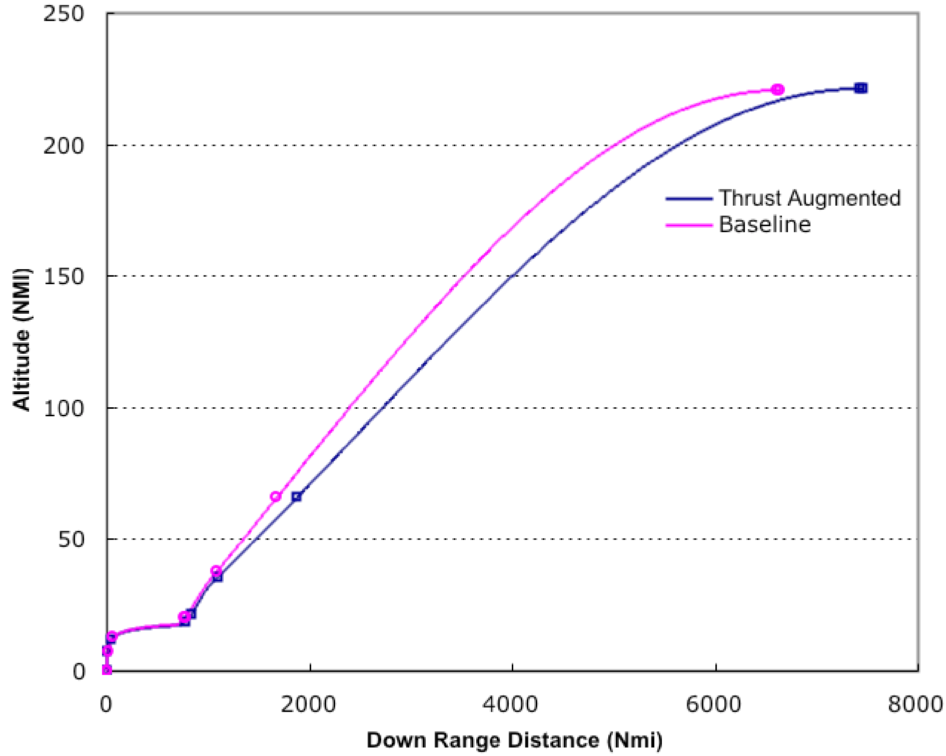

Figure 7. Altitude vs. Down Range Distance

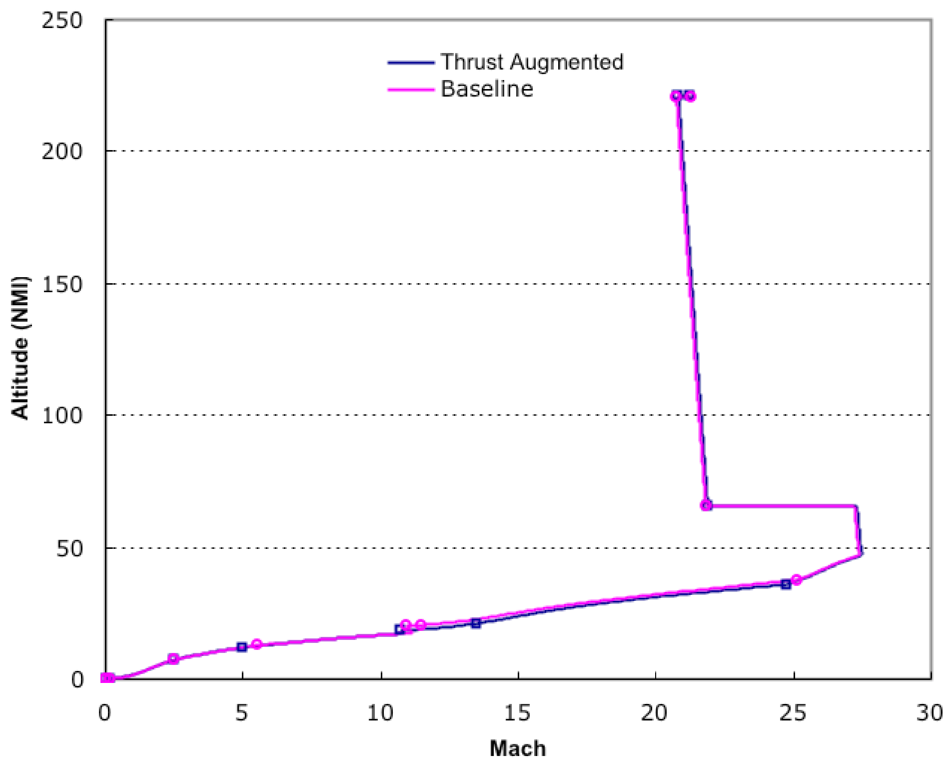

Figure 8. Altitude vs. Mach

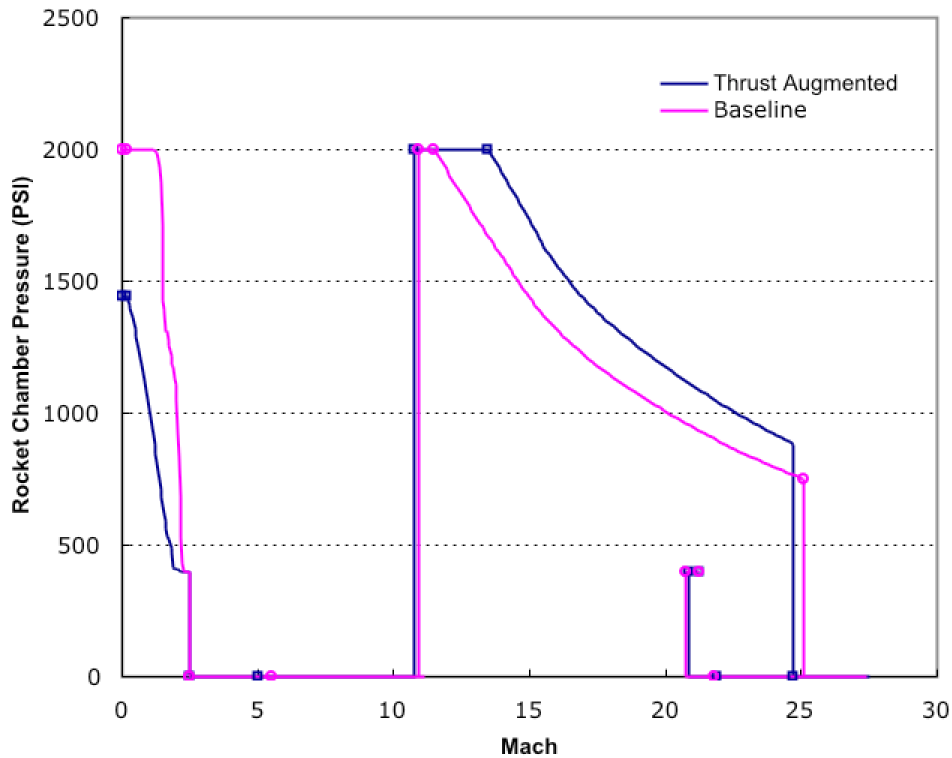

Figure 9. Chamber Pressure vs. Mach

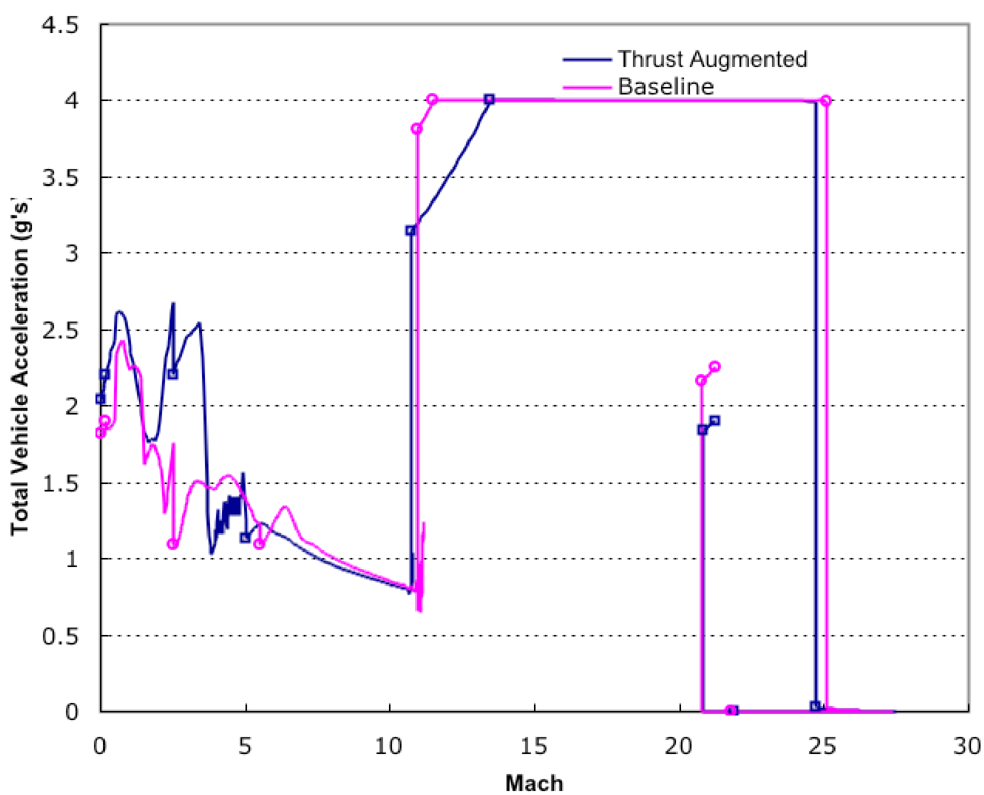

Figure 10. Acceleration vs. Mach

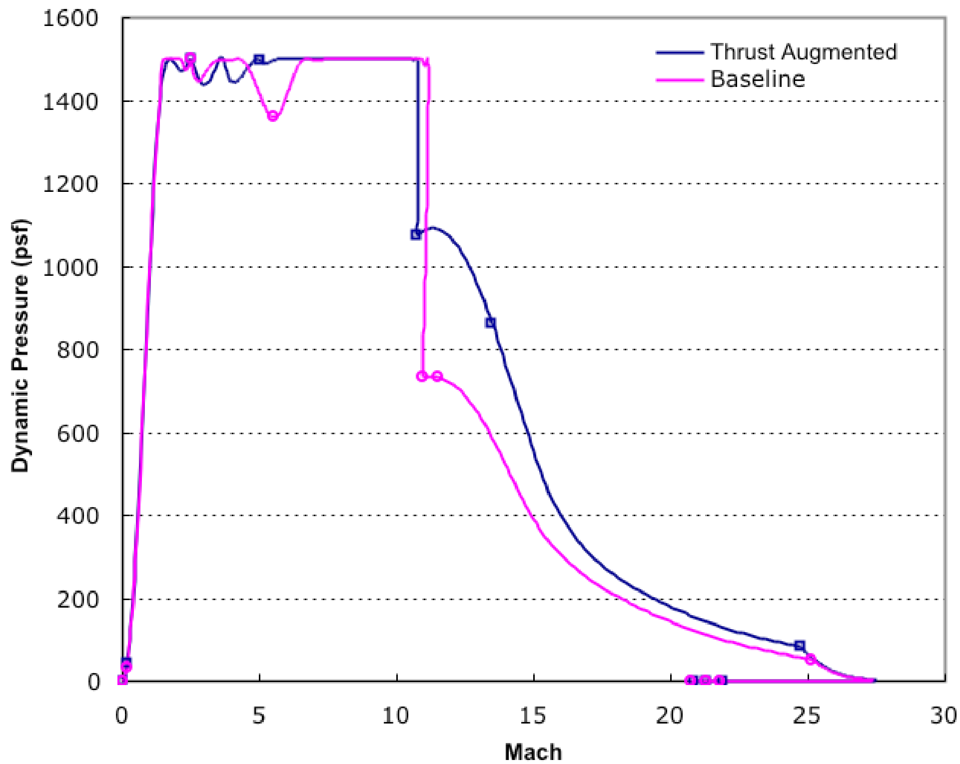

Figure 11. Dynamic Pressure vs. Mach

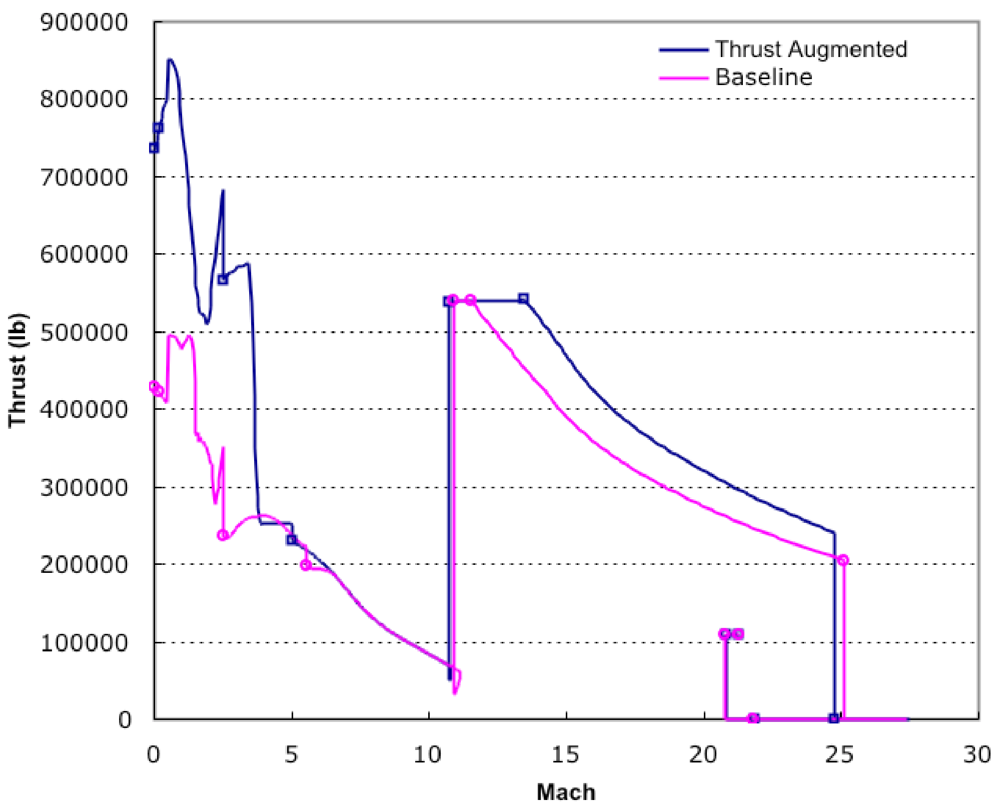

Figure 12. Total Vehicle Thrust vs. Mach

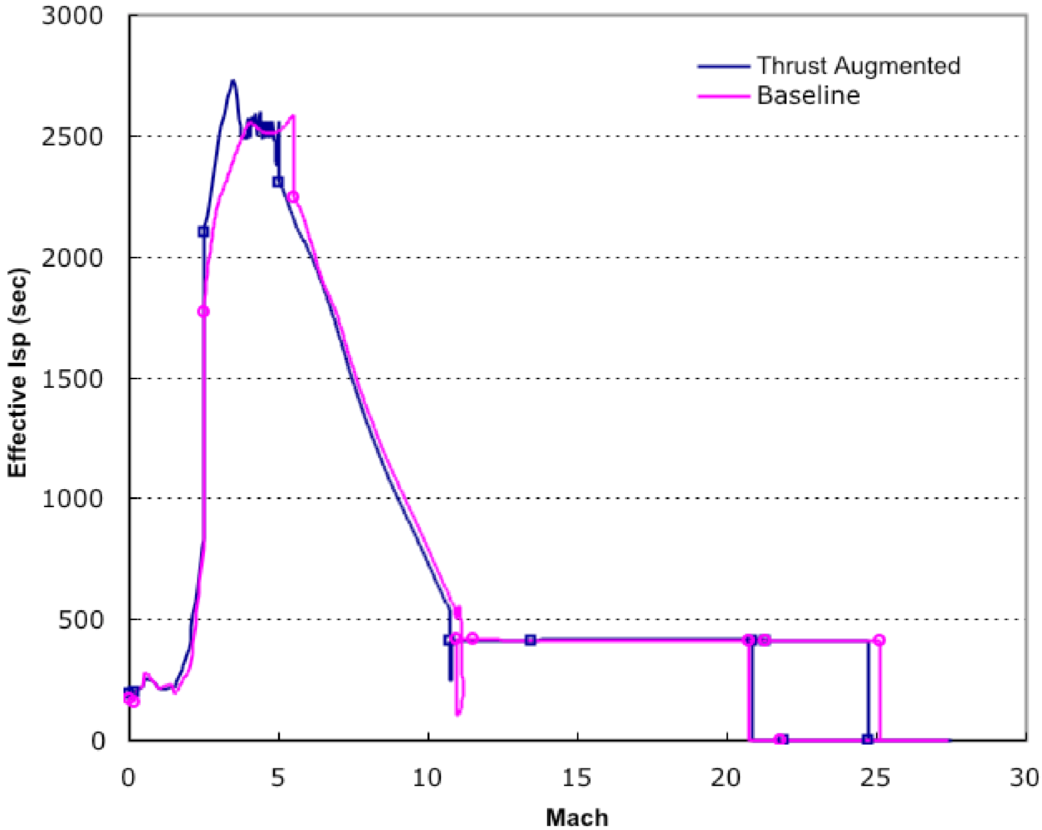

Figure 13. Effective Isp vs. Mach

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13. ABSTRACT ***(Maximum 200 words)***

A goal of the GTX effort has been to demonstrate the feasibility of a single stage-to-orbit (SSTO) vehicle that delivers a small payload to low earth orbit. The small payload class was chosen in order to minimize the risk and cost of development of this revolutionary system. A preliminary design study by the GTX team has resulted in the current configuration that offers considerable promise for meeting the stated goal. The size and gross lift-off weight resulting from scaling the current design to closure however may be considered impractical for the small payload. In lieu of evolving the project's reference vehicle to a large-payload class, this paper offers the alternative of using solid-rocket motors in order to close the vehicle at a practical scale. This approach offers a near-term, quasi-reusable system that easily evolves to reusable SSTO following subsequent development and optimization. This paper presents an overview of the impact of the addition of SRM's to the GTX reference vehicle's performance and trajectory. The overall methods of vehicle modeling and trajectory optimization will also be presented. A key element in the trajectory optimization is the use of the program OTIS 3.10 that provides rapid convergence and a great deal of flexibility to the user. This paper will also present the methods used to implement GTX requirements into OTIS modeling.

14. SUBJECT TERMS

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